

Blast Resistant Design of Explosive Containment Chamber

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Abstract

Hypervelocity projectile rail guns require instantaneous electrical switching of extremely high energies. To achieve the necessary switching speed, cord explosives are used to drive strips or slats out of aluminum switch plates creating precise gaps which allow the electrical energy to arc. This paper describes the dynamic design of aluminum containment vessels for the explosive switches.

The switching mechanism for the rail gun consisted of four 30" x 84" switch plates for main current diversion and two final interrupt switches to dissipate any current remaining after the test. Configuration of the electrical bus bars attached to the switches could not be interrupted which required separate half cylindrical vessels. Large magnetic fields produced by nearby inductors required that the vessels be fabricated from aluminum. Use of this material for blast loads produced special problems with fabrication and structural response which necessitated close examination of the localized stresses, especially in areas which were welded. The containment vessels were designed for a test frequency of two per week for a 5 year life. Due to the testing frequency, the vessels had to be easily removed for cleaning between shots.

Cord explosive used to open the switches consisted of 8 lines of 100 gr./ft PETN. The blast pressures and fragments produced by detonation of the cord were required to be contained to protect personnel and equipment. In addition to the blast loads from the explosives, the electrical energy passing across the switch created additional blast pressures. It was found that the energy per unit length of the switch arcs approximated that of common lightning bolts. Pressure prediction formulas for this strength of energy dissipation were used to predict blast loads.

The paper describes design requirements, load prediction techniques, structural analysis methods, material response, and operational considerations.

Introduction

Design of structures and equipment to contain the effects of explosions presents some very unique challenges to the designer, especially those involving repeated application of the load. Designs for accidental explosions are generally able to employ plastic response to absorb the load and permit at least moderate damage. Elements which are required to remain operational under repeated loads however, must remain elastic under the design load with a high degree

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of confidence that resistance to subsequent load will not be impaired. Meeting these design goals can be difficult if the loads are high and space is limited. This paper describes a project which introduced geometric, material and operational constraints which required innovative approaches to achieve a workable design.

Hypervelocity projectile rail guns require instantaneous electrical switching of extremely high energies. To achieve the necessary switching speed, cord explosives are used to drive strips or slats out of aluminum switch plates creating precise gaps which allow the electrical energy to arc. Containment of blast pressures and fragments is necessary to prevent injury to personnel and damage to equipment. A partial view of a typical containment chamber and explosive switch is shown in Figure 1.

Requirements

Containment vessels for this project were required to be installed in one-half sections because the switches were located on each side of the bus bar system as shown in Figure 2. A complete cylinder has very good resistance capabilities even for thin sections; however, the use of half sections of the cylinder reduces this effectiveness and produces high material stresses at the connection points.

Near total containment of the explosion effects was required to limit damage outside the chambers. A large amount of soot is produced during the switching process and leakage of these products would produce significant maintenance problems for the surrounding equipment. Total containment produces a large quasi-static pressure in the vessels due to the limited vent area. Structurally, this required a resistance which exceeded the peak gas pressure. Space limitations prevented use of a large containment vessel to increase the volume and reduce the gas pressure.

The chamber was required to resist the effects of an operating basis event with elastic response including energy of the cord explosives and release of the magnetic energy. The design life of the chambers was five years with a test frequency of two per week. Ease of installation was an important consideration for achieving this test frequency. It was especially important for the user because each test shot would require changing six chambers to replace the explosive switches. Bolted configurations were permitted but the number of bolts was to be minimized.

The presence of large magnetic fields produced by adjacent equipment precluded the use of ferrous materials with the exception of bolts. This requirement was one of the most challenging due to the high blast loads involved. Aluminum was used to satisfy this criteria but it presented significant problems with material strength, especially at welded connections.

Blast Loads

Each explosive switch houses eight lines of 100 grain/foot PETN. Each line is end-detonated simultaneously, driving thin sections of the aluminum plate out in strips to create a gap and

produce the required electrical arc. This arcing process releases approximately 1.1 megajoule (MJ) of magnetic energy. This release causes a rapid pressure rise on the containment chamber due to heating of the air and creates a long term, quasi-static load. It is in addition to the quasi-static load produced by the cord explosives.

The load variation at each location within the containment was significant at any given point in time. Cord explosives produce a shock wave which expands radially from its axis as the explosion propagates along the axis. Interaction of blast waves from adjacent cords also produces a complex blast environment within the chambers. Given the number of variables involved, it was determined that accurate prediction of the true blast loads was not feasible and that a simplified method for prediction of loads was required.

The initial method selected consisted of treating each cord line as a separate charge and computing the reflected pressure and impulse from each at several locations within the chamber. A 20% safety factor on the design charge weight was selected to provide the required conservatism. Impulse from each charge was added at each location to predict the total load. Magnetic energy released during the arcing process was converted to an equivalent weight of TNT and added to the weight of the cord explosives for load prediction. The equivalent weight of the magnetic energy is approximately 50% of the cord explosives weight which is a significant contribution to the blast loads.

Distance to each point of interest with the chambers was computed and a scaled distance was determined by dividing by the cube root of the total equivalent explosives weight for a unit length of switch. To predict the loads, curves for side-on pressure and impulse for hemispherical surface bursts were used (Reference 1). The loads were converted to reflected load based on pressure level and angle of incidence. Peak pressure and impulse were averaged over the chamber surface for structural response calculations.

Since the cord detonation propagates down its axis, the blast wave from a unit charge cannot expand three dimensionally, only in two dimensions as shown in Figure 3. The load prediction curves used are based on hemispherical expansion rather than radial expansion, thus a modification to the method was required. A 12" section of cord and magnetic energy was lumped together as a single charge to compute the shock loads at any point along the length to account for the difference in expansion. Scaled distance from each point was computed based on this pseudo charge and the surface burst curves were again used.

Some modifications were made to this method during the course of the project to account for the fact that most of the magnetic energy release occurs in the middle one-third of the switch. Additionally, peak pressure and impulse values were multiplied by 1.75 to account for structural response to multiple reflections within the chamber.

Detonation of the explosive cord does not occur at the same time as the release of the magnetic energy. Arcing does not occur until a significant amount of the aluminum strip has been ejected. Initiation of the cord explosives at opposing ends creates shock waves traveling toward each other at approximately 8000 fps. It was assumed that arcing begins when the

waves meet. Since the burn rate of the explosives cord is on the order of 22,000 fps, the explosive detonation will be completed prior to the magnetic energy release. Ejection of the strips will lag in time relative to the shock front and it is assumed that the center 1/3 of the switch is intact when the opposing waves meet. Release of the magnetic energy was assumed to occur in this region. Assuming the shock fronts travel at the same velocity, the lag time will be equal to the time it takes for the front to travel 1/6 of the length of the switch. These considerations formed the basis for separating the equivalent TNT weights for computing pressure and impulse. To simplify the problem for analysis, impulses were added and assumed to occur at the same time.

A second method for determining blast loads from the magnetic energy release involved the use of pressure prediction equations for lightning bolts. The energy per unit length of the switch is on the order of 500,000 J/m while a typical lightning strike is around 100,000 J/m. Reference 2 presents a discussion of pressure waves from lightning and presents equations for prediction of pressure versus standoff distance. Results of these calculations produced significantly lower loads for the magnetic energy release than converting to an equivalent weight of TNT and lumping a tributary length as described above. Impulse equations were not provided for lightning therefore it was necessary to rely on explosive equivalency for these predictions. Since the pressures from the magnetic energy were considerably lower, the TNT equivalent weights were separated and peak pressure was predicted for the cord weight only. Total impulse was computed based on the combined TNT equivalent weight.

Quasi-static pressures were predicted using the methods described in Reference 1. A total equivalent explosives weight was computed from the cord and magnetic energy. The weight/volume ratio for the entire chamber was computed and used to determine the peak pressure. This load was combined with the shock loads to form the design basis loads.

Configuration

Several configurations for the chambers were analyzed in the initial phases of the project to determine the design which best satisfied the criteria. These configurations are depicted in Figure 4. The first section analyzed was intended to provide a large volume for gas expansion while maintaining the necessary spacing for connection bolts which was fixed by the bus design. Analysis showed that very high stresses were produced at the junction of the cylinder and flange making the required thickness excessive.

The second configuration was semicircular with a stiffened flange. The third section was evaluated was a variation on the semicircular design with an extension at the centerline to increase the standoff distance from the switch to the chamber wall. It also increased the total volume of the chamber which reduced the peak quasi-static pressure. This section was ultimately selected for the final design with 2:1 elliptical heads for the top and bottom. The rectangular section provided good standoff and volume; however, the loads had to be resisted in flexure and the required thickness was too great.

Attachment of the chamber to the bus bar system presented several difficulties. Primary

among these were the high flexure stresses produced by dynamic reactions from the chamber walls. Use of a flat flange bolted to the bus bars resulted in large prying forces requiring thick flanges and close bolt spacing. To reduce these stresses, different attachment methods were analyzed as shown in Figure 5.

Pinned connections were the best solution structurally because the flexural stresses at the flange were greatly reduced. Most of these solution however, required a very close bolt spacing which made installation difficult and time consuming. A track system was selected as the best solution to the stress problem and the operational requirements. The track rail remains permanently attached to the bus bar and the chamber slides vertically in the track. The lower head of the chamber is permanently attached to the lower bus support and a bolted flange is provided to join the removable section of the chamber to the lower head. This arrangement minimizes the number of bolts the operators must secure during installation of the chamber and eliminates many alignment problems. A bulkhead is formed above the bus to secure the top portion of the chamber.

Gaskets are provided in the track which will be compressed under load to prevent leakage of combustion products. A cross section of the final configuration is shown in Figure 6. An external view of the chamber is shown in Figure 7.

A fragment liner will be installed on the interior face of the cylinder to reduce damage from fragments and debris from the switch slats as they are driven out by the explosive. A high density polyethylene was considered along with a stranded aluminum product. An advantage to the aluminum is its ability to reduce peak pressure loads on the chamber by absorbing the blast.

Material Properties

Several aluminum alloys were investigated for construction of the chambers. Stainless steel was also evaluated but was not selected because it can become magnetic under appreciable cold working. Since the cylinder and heads will be formed, significant cold working will occur. Primary considerations for the alloys evaluated were strength, weldability, machinability and ductility. Alloys considered were divided into two categories: heat treatable and non-heat treatable. From the heat treatable group, 6061-T6 provided the best choice for the design. In the non-heat treatable group, 5454-H34 was best suited for the chambers. Both materials have similar strength and forming characteristics but the 5454-H34 has a higher free bend elongation. It is also approved for ASME vessels which is not critical to this application for certification but is highly desirable for this type of construction. The chambers will be heat treated to relieve residual stresses but it was determined that heat treating to recover lost strength would not be required. 6061-T6 material was ultimately selected.

Dynamic properties for aluminum are not significantly different than static properties. Unlike carbon steels which exhibit an increase in strength with increasing strain rate, the dynamic yield of aluminum alloys is approximately equal to the static yield strength.

The welded strength of the chambers was a major consideration for the design. Welding of aluminum can have a dramatic effect in reducing the strength of the material surrounding the weld. For this reason, allowable stresses within one inch of the weld, the heat affected zone, was reduced by 50%. Because the chambers will have a welded connection at the shell/flange junction where high material stresses were predicted, design of this joint required close scrutiny. To reduce the weldability problem, a connection was developed which located the weld away from the joint where stresses were lower and the reduction in strength was acceptable.

Structural Analysis

The containment chambers were analyzed for dynamic loads by computing single-degree-of-freedom (SDOF) properties and numerically integrating the equations of motion while applying transient loads. These properties were obtained by static analyzing the chamber for a unit internal pressure and obtaining peak stress and deflection. This pressure was scaled to arrive at a resistance and stiffness. Since the chambers had to remain elastic, this approach was possible.

A finite element model of the cylinder quarter section and flange was developed to determine local stresses caused by the bolts, flanges and stiffeners used in the various configurations. Typical stress contours from this analysis are shown in Figure 8. Shell elements were used for the cylinder and 3-D solids were used for the flange. The elliptical heads were analyzed independently to determine SDOF properties; however, restraining effects of the cylinder at the springline were included. Additionally, axial loads developed in the heads were included in the cylinder analysis. A 2-D dynamic response of the cylinder section was also performed for the final chamber design to verify the accuracy of the SDOF analysis.

Since the chambers are inherently stiff, the maximum response of the sections occurred very early in the load-time history. This meant that the chamber was responding primarily to the shock loads with the quasi-static loads having less effect. High pressures occurring at close standoffs tended to drive the design by producing high local stresses. Inclusion of a liner material is highly desirable to reduce the peak pressures.

Conclusions

Design of containment chambers for explosively actuated switches presents interesting challenges to develop structurally efficient configurations which meet all design requirements. Prediction of blast loads for the chambers in this project necessitated the use of innovative approaches because of the complexity of the blast environment produced by the cord explosives and magnetic energy release.

Operational constraints regarding connections for the chambers were a major driver in the design. Limitations on material types caused by the high magnetic fields also presented significant problems for the design. The final design represented the best alternative for the criteria presented and produced a workable solution.

References

1. "Structures to Resist the Effects of Accidental Explosions" (Revision 1), Army TM5-1300, Navy NAVFAC P-397, Air Force AFR 88-22, Department of Defense Explosives Safety Board, Alexandria, Virginia, November 1990.
2. Uman, M.A.; Lightning; Dover Publications, 1969.

Figure 1 View of Switch and Containment

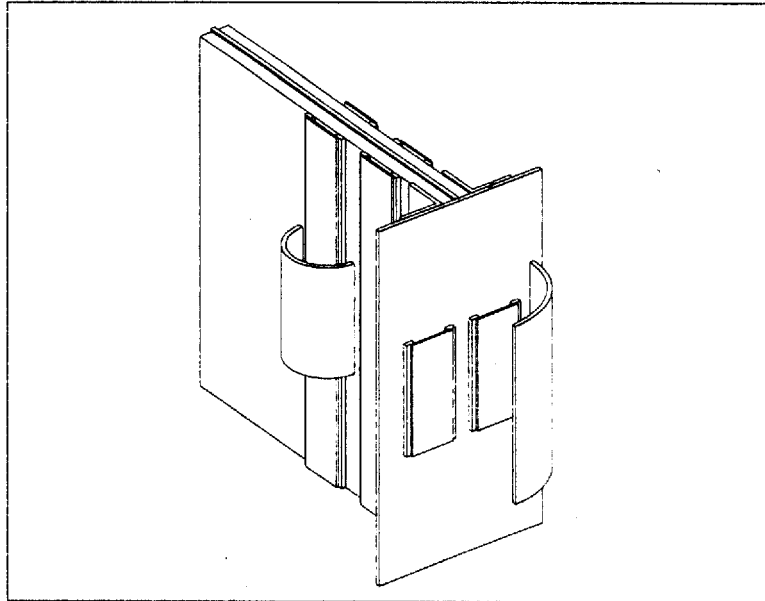


Figure 1 View of Switch and Containment

Figure 2 Cross Section of Switch and Containment

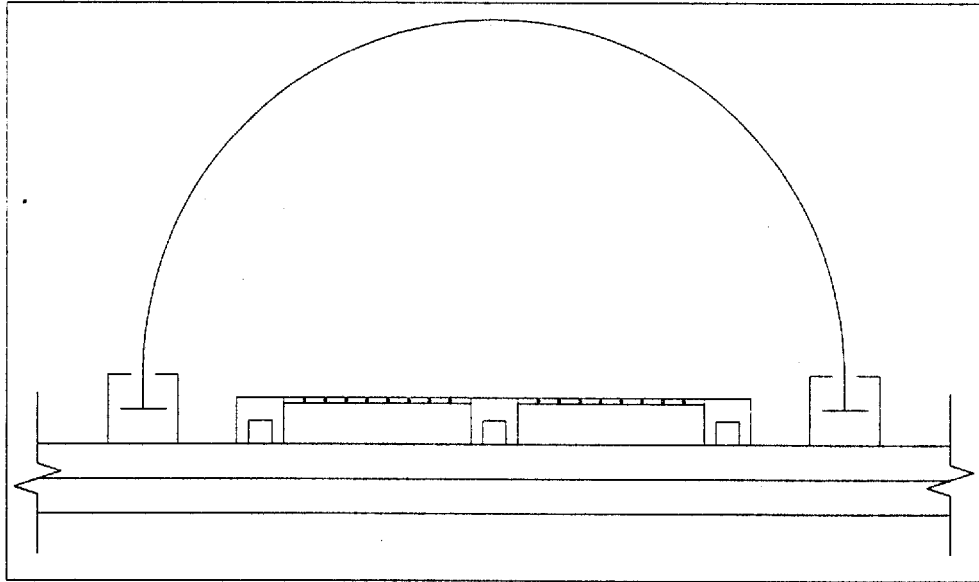


Figure 2 Cross Section of Switch and Containment

Figure 3 2-D vs. 3-D Expansion

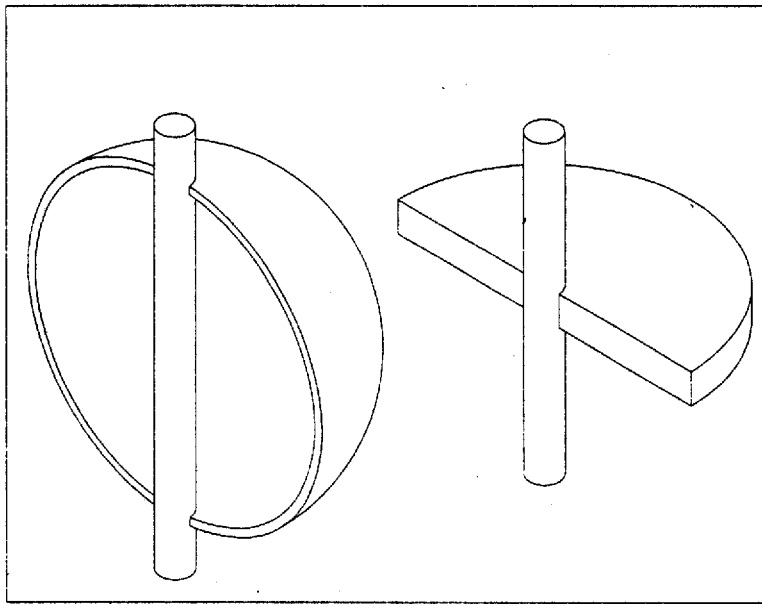


Figure 3 2-D vs. 3-D Expansion

Figure 4 Cross Sections Evaluated

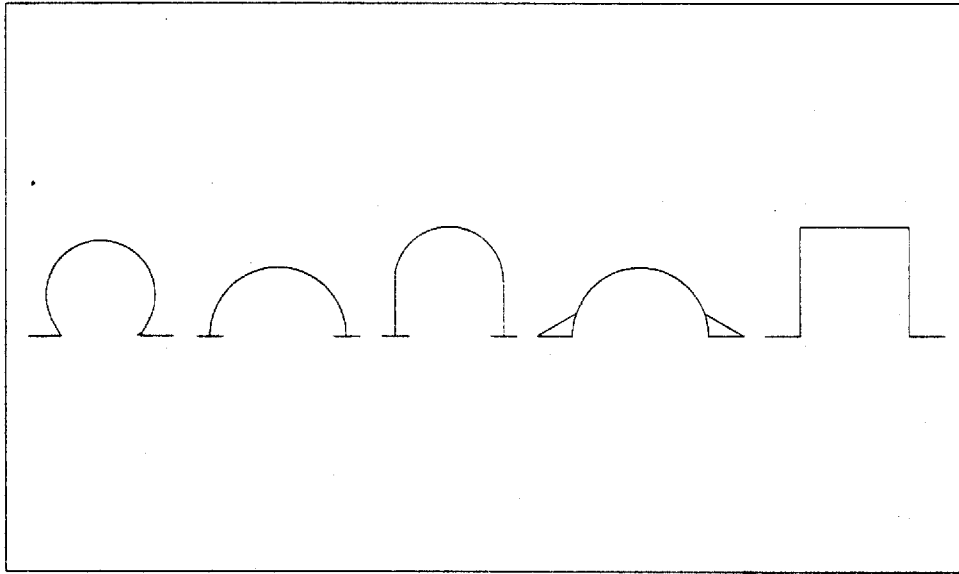


Figure 4 Cross Sections Evaluated

Figure 5 Connections Analyzed

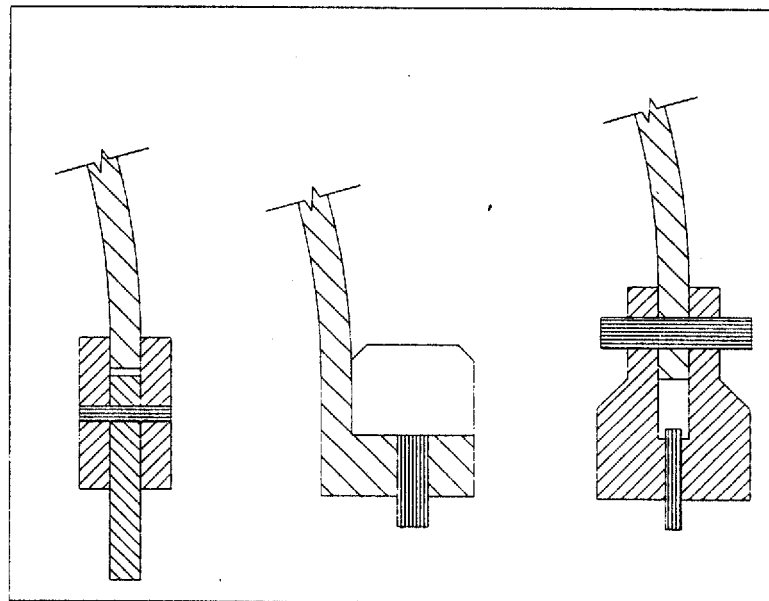


Figure 5 Connections Analyzed

Figure 6 Final Cross Section

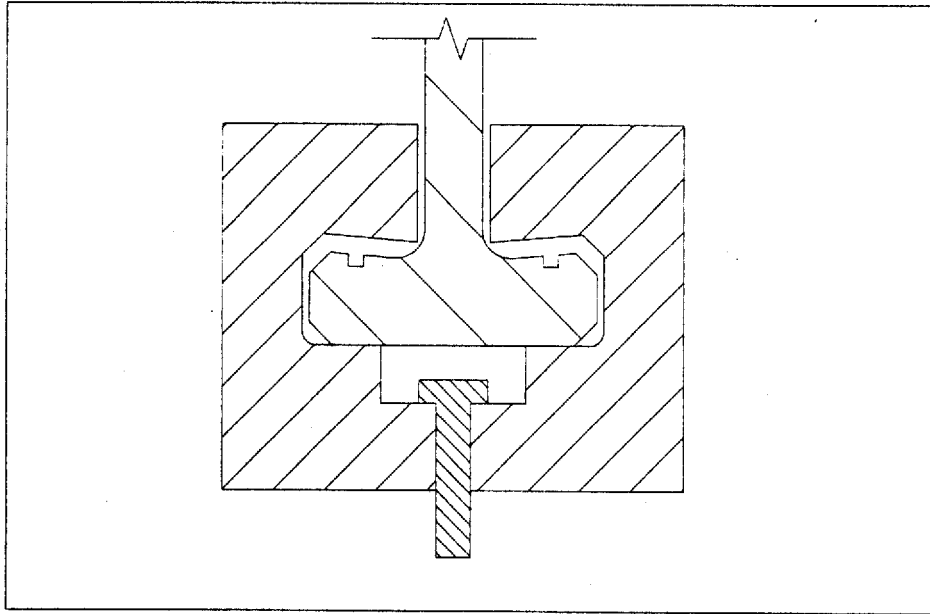


Figure 6 Final Cross Section

Figure 7 Containment Chamber

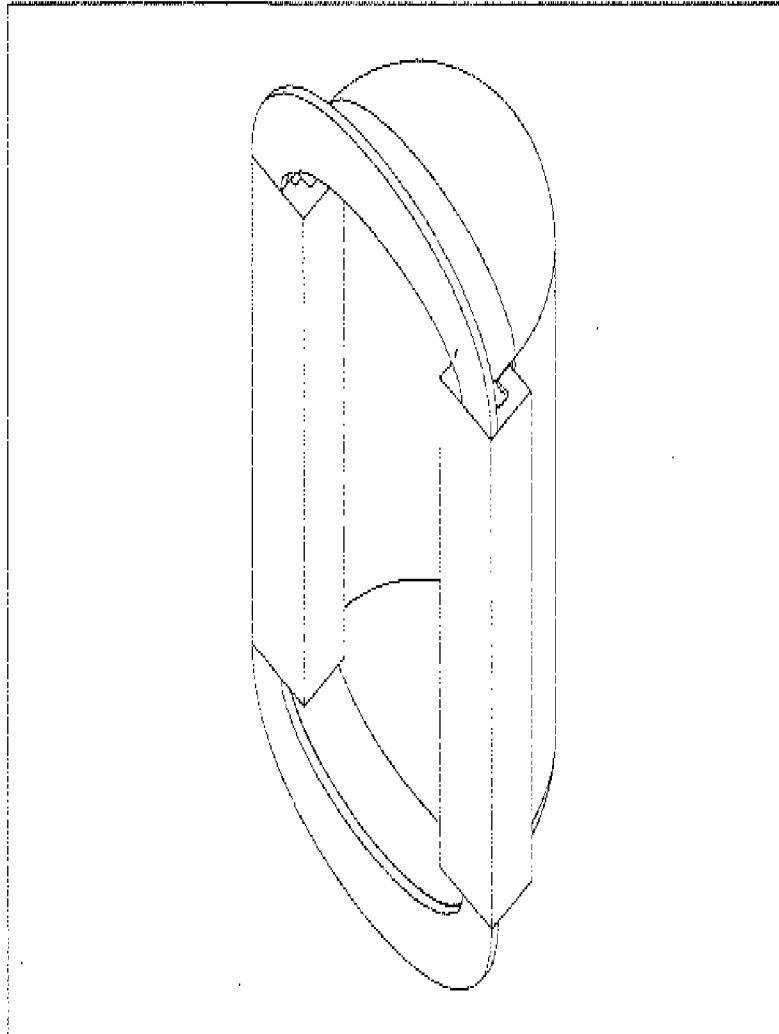


Figure 7 Containment Chamber

Figure 8 Stress Contours Flange

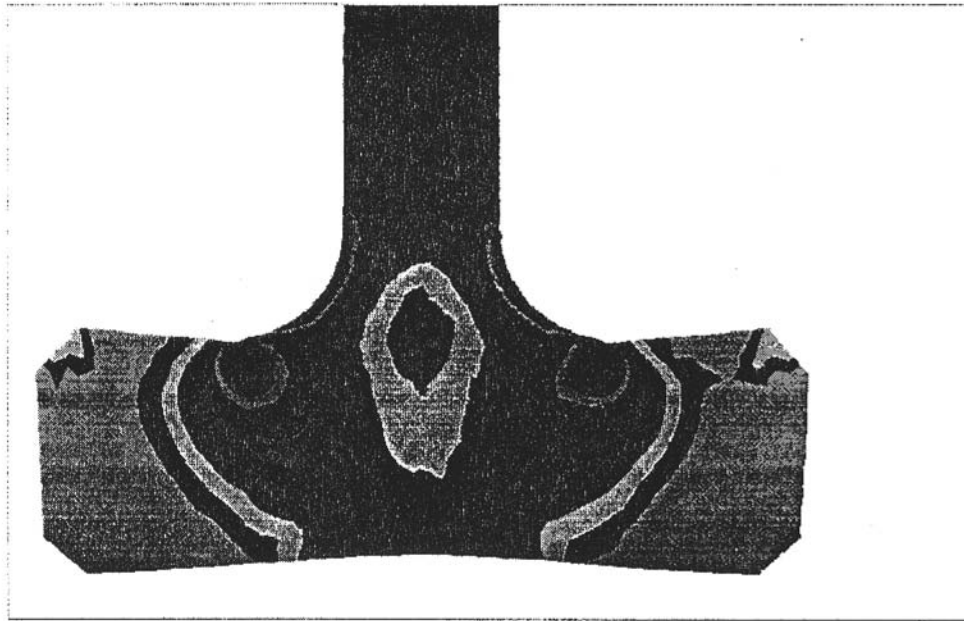


Figure 8 Stress Contours Flange